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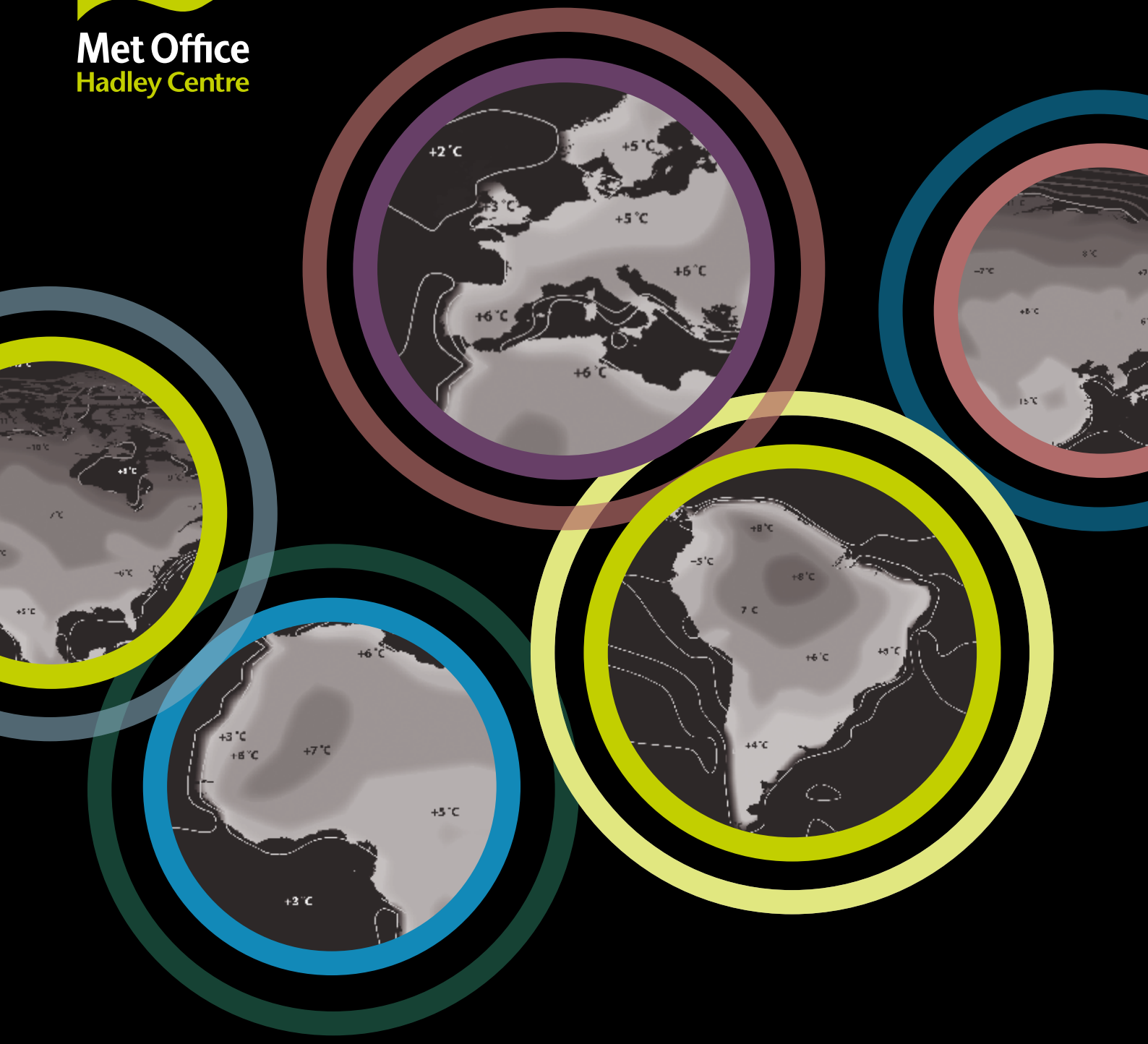

Science

Driving our response to climate change

DEPARTMENT OF ENERGY & CLIMATE CHANGE

defra
Department for Environment Food and Rural Affairs

Met Office working in partnership

Informing mitigation

The evidence has never been stronger — climate change is happening and poses significant risks to life on Earth. Continuing scientific research is playing a crucial role in helping us to understand these risks, as well as mitigate and adapt for them.

Science has provided us with overwhelming evidence of man-made climate change, providing a clear and impartial response to those who cling to doubts. Science shows how our climate has already changed and how it may change in the future.

Ultimately, it is this science that will guide us in an effective response to the challenges we face and minimise the impacts of climate change. The evidence points to early and deep cuts in greenhouse gas emissions to limit the long-term consequences.

Here, we focus on the latest observations of climate (including warming trends), potentially dangerous future impacts and the effect of global and sectoral mitigation options.

"Science must drive our response to climate change"

Ban Ki Moon at the World Climate Conference 3, September 2009

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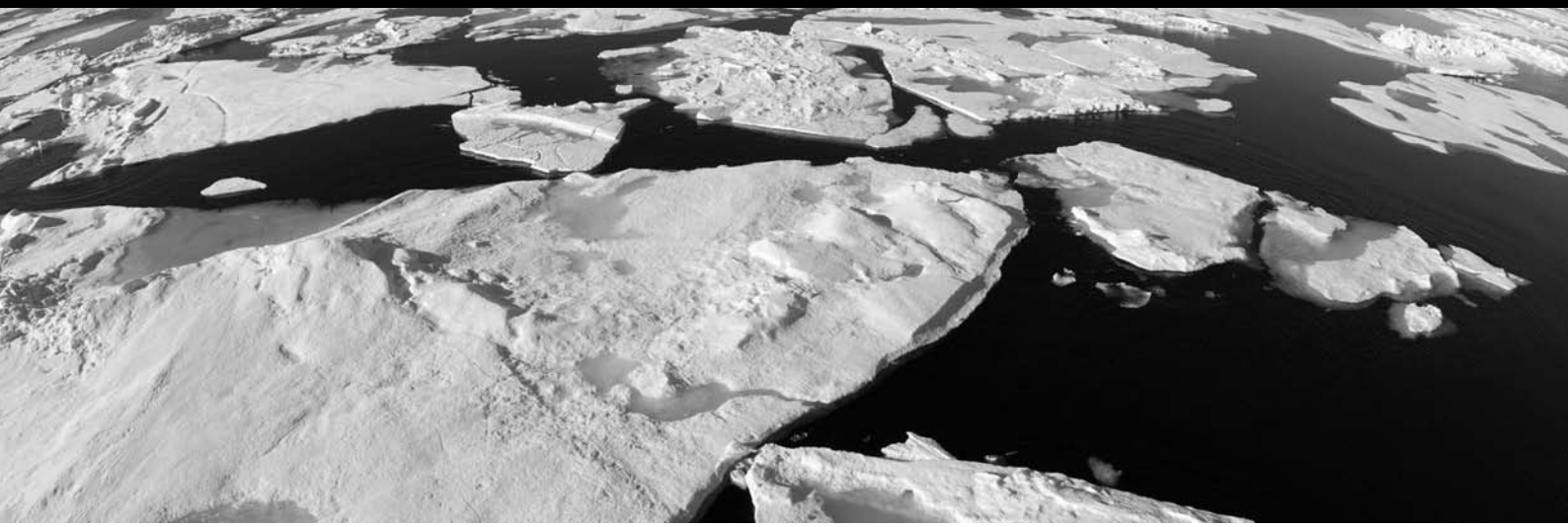
Observations



- 2009 (to September) is the fifth warmest year in the 160 year HadCRUT3 global temperature record
- The Earth's temperature has risen by 0.75 °C over the last century and the period 2000–2009 was warmer than the 1990s
- Observations are consistent with ongoing warming of about 0.15 °C per decade since the mid-1970s
- All years from 2001 have been in the top eleven warmest on record
- At least half of all years after 2009 are expected to be hotter than 1998 — to date the warmest year

Observations of our climate are vital in assessing how global warming has already affected our planet and, when combined with model projections, how it may affect us in the future. Here we present the latest information on key aspects of our current climate, from the global temperature trend to the state of Arctic sea-ice.

Data show recent years have remained very warm compared to the historical baseline, with some years being close to the global annual temperature record set in 1998. This is despite a relative slowdown in global warming over the past decade due to natural variations in our climate. These variations are affected by a number of factors, such as changes in ocean currents and solar activity, and can create climate fluctuations over years or even decades. They can influence all aspects of our climate, from global temperatures, to Arctic sea-ice extent and many other indicators of climate change.

The variations mean we do not expect to see consistent increases in global temperature from year to year, or decade to decade under climate change. Instead we must focus on long-term trends, and observations show a clear trend of warming for the past 40 years. Current projections suggest that the relative slowdown in this trend over the past decade is likely to end, with more rapid warming to resume from 2010 onwards.

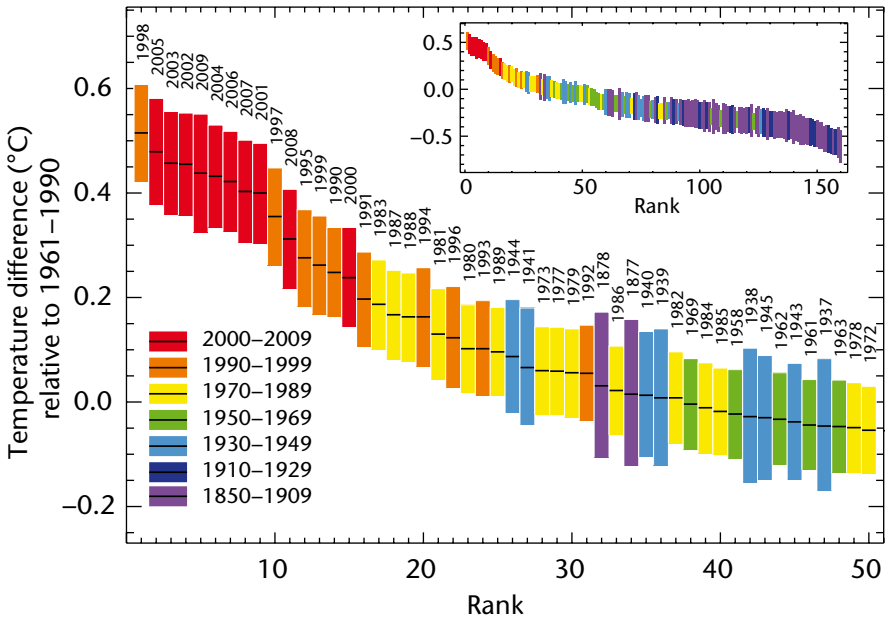


Figure 1. The fifty warmest years in the global average temperature series shown in rank order from warmest on the left to coolest on the right. The temperatures are shown as differences from the average for the period 1961–1990. Vertical coloured bars represent the temperature uncertainty range. The inset diagram shows the global average temperature for all years from 1850 to 2009 in rank order. The HadCRUT3 global average temperatures are produced jointly between the Met Office and the Climatic Research Unit at the University of East Anglia. (Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD. Uncertainty Estimates in Regional and Global Observed Temperature Changes: A New Data Set from 1850, J.G.R., Vol 111, D12106, doi:10.1029/2005JD006548, 2006).

YEAR TO DATE

Global average temperature in 2009 (to September) is 0.44 °C above the 1961–1990 average, making it the fifth warmest year in the 160 year HadCRUT3 record. The first half of 2009 was cooler due to the influence of a La Niña, which brings cool water to the surface of the Pacific Ocean. A shift to El Niño conditions followed for the second half of the year, warming the Pacific Ocean's surface and raising global temperatures. This warming influence is expected to extend through the winter, which could push up the final global temperature for 2009.

Figure 1 shows 2009 (to the end of September) ranked fifth in the series of years. The figure also shows how years since 1990 have dominated the higher rankings.

WARMING TRENDS

In 1998 the world experienced the warmest year on record — with temperatures pushed up by a particularly strong El Niño. No year since has beaten this record, leading some to claim global warming has stopped or even that our climate is cooling. A closer look at the figures reveals many years have been close to the 1998 record, such as 2005. A longer-term view also reveals that the trend in warming temperatures seen for the past few decades continues. The period from 2000 to 2009 was on average 0.17 °C warmer than the 1990s. Furthermore, all years since 1998 fall within the top 15 warmest on record.

The rate of warming observed over the last ten years is lower than previous decades. However, this relative slow-down in warming is not surprising — even against a background of increasing greenhouse gas emissions — because of variability within our climate.

Varying rates of warming were observed through the 1970s, 80s, and 90s. Recent Met Office research found climate simulations featured near-zero or negative global temperature trends for one in every eight decades. Hence the strong warming in some decades and slower warming in the last decade are both entirely consistent with the model predictions of climate change. In the long-term, temperatures are expected to continue to rise.

THE NEXT 10 YEARS

Our decadal forecasts provide more detailed projections over a shorter time by predicting some aspects of natural variability in addition to the warming trend from greenhouse gases. By starting the forecast from current observations, these predictions provide an improved picture of what's expected. They have already demonstrated a higher level of accuracy over the short term than projections based solely on changes in greenhouse gases.

According to the Met Office decadal forecast, at least half of the years after 2009 are expected to be warmer than the 1998 record. This will continue the observed ongoing warming, which has averaged about 0.15 °C per decade since the mid-1970s.

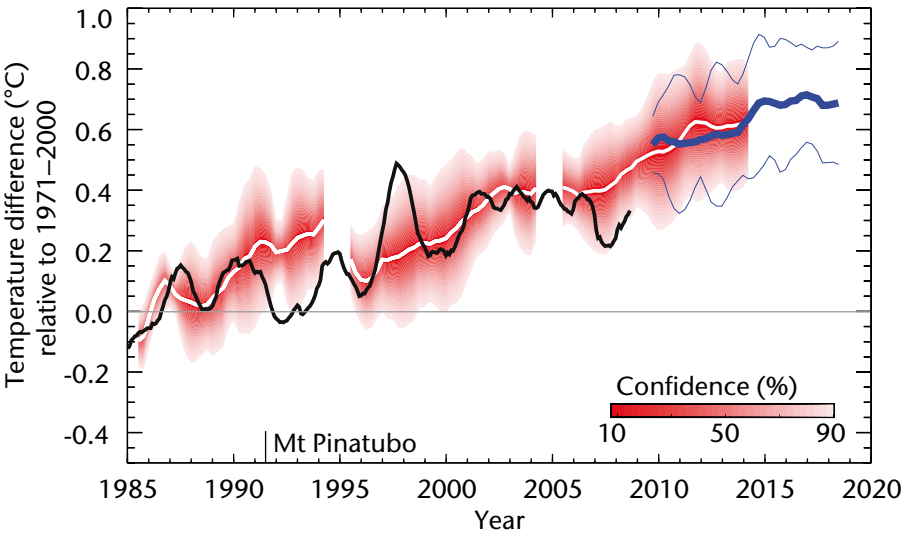


Figure 2. Observed (black) and predicted global average annual surface temperature difference relative to 1971–2000. Previous predictions starting from June 1985, 1995 and 2005 are shown as white curves, with red shading representing their possible range — the observations are expected to lie within the shading 90% of the time. The most recent forecast (thick blue curve with thin blue curves showing range) is the average of the forecasts starting from June and September 2009. Mt Pinatubo is shown as its eruption was followed by a temporary drop in global temperatures.

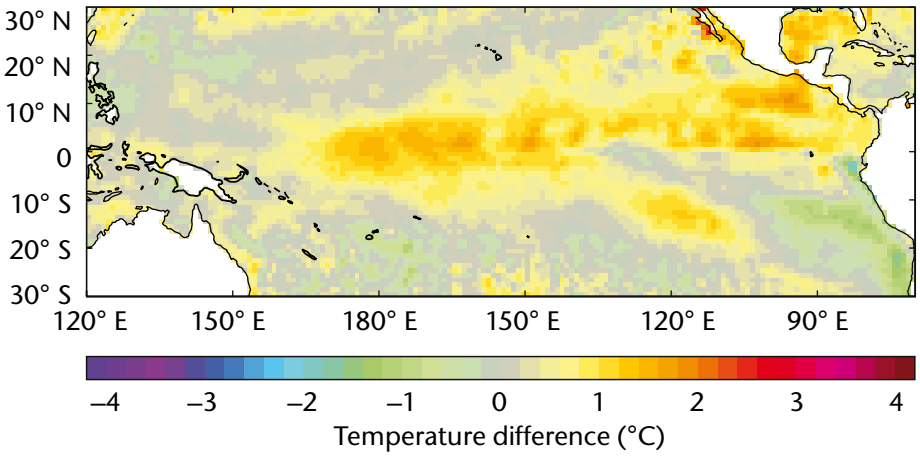


Figure 3. Tropical Pacific Ocean sea surface temperature differences (˚C) for October 2009 relative to the October average for 1971–2000.

- A strengthening El Niño rapidly increased Pacific Ocean surface temperatures in 2009. This is expected to last through to winter 2009–10
- Arctic sea-ice is declining at a rate of 0.6 million km² per decade, an area approximately the size of Madagascar
- The Arctic is projected to become ice-free later in the century
- Climate change is affecting the probabilities of extreme weather events occurring

EL NIÑO

El Niño is the warm phase of a natural fluctuation in the Earth's climate system, known as the El Niño Southern Oscillation (ENSO). During this phase, sea surface temperatures in the tropical Pacific Ocean warm significantly. Its counterpart, La Niña, sees an opposite effect — with temperatures cooler than normal. Each event normally lasts 12–18 months, with fluctuations between warm and cold phases happening every few years, but not at regular intervals. ENSO affects the strength of trade winds and the location of the strongest rainfall in the Pacific region, and is a key driver of climate variability across the globe. It has a discernible influence on global average temperature, with El Niño years being warmer than those years with a La Niña influence.

In early 2009, surface temperatures in the tropical Pacific were cooler than average due to a La Niña, which became established late in 2007. Temperatures warmed rapidly through the year, however, and a weak El Niño was present towards the end of 2009, with the equatorial Pacific sea surface temperature 0.5 to 1.5 °C above average. The Met Office Seasonal Prediction model, GloSea4, indicates the El Niño will last through the 2009–2010 winter.

ARCTIC SEA-ICE

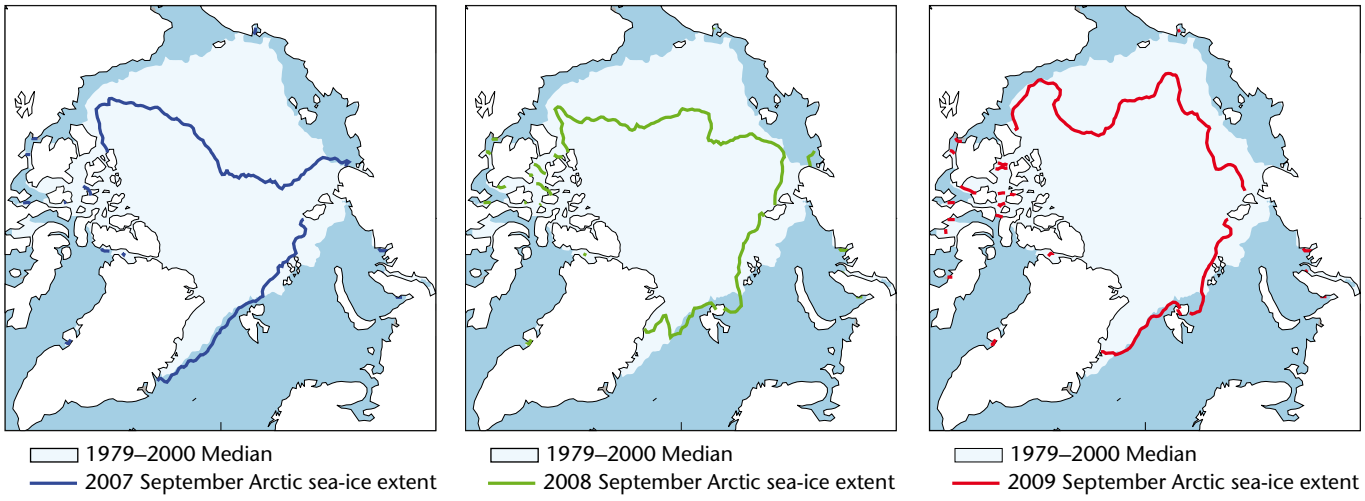
The extent of Arctic sea-ice has been decreasing since the late 1970s, reducing by 0.6 million km² every decade. There is considerable variability within this decline, however, which means the extent of the sea-ice has not reduced at a constant rate.

For example, in 2007 there was a dramatic single year decline, with the sea-ice reaching an all time low of 4.1 million km² — about 39% less than the 1979–2000 average of 6.7 million km². Scientific analysis has shown this was in part due to the Arctic's highly variable weather patterns.

Since the record low of 2007, a recovery has been observed in the sea-ice extent. In 2008, the minimum was 4.5 million km², and the 2009 minimum was 5.1 million km². While this marks an increase from 2007, these years were respectively the second and third lowest recorded sea-ice extents since the record began in 1979. Both years are still within the expected trend of long-term decline.

The trend of decline and the observed variability, including the minimum extent observed in 2007, are both consistent with climate modelling from the Met Office. Our model shows that ice invariably recovers from extreme events,

Figure 4. Arctic sea-ice extents for September 2007, 2008 and 2009 from the HadISST data set.



Research is ongoing to develop a system for attributing extreme weather events as they happen, providing an almost immediate assessment of how likelihoods have been affected by climate change.

such as 2007, but will continue to reduce in the long-term as global temperatures rise. If the rate of global temperature rise increases, then so will the rate of Arctic sea-ice decline. The first ice-free summer is projected to occur later this century, although the precise year is uncertain. The Met Office model projects this will happen between 2060 and 2080 if emissions continue along a business as usual pathway. However, experiments suggest that — unlike many other impacts — this change may be reversible.

WEATHER EXTREMES AND CLIMATE CHANGE

A higher frequency and increased intensity of extreme weather events are some of the projected consequences of climate change. There has been considerable debate, however, about whether specific events can ever be attributed directly to global warming. This question was raised again in 2009 over events such as the Australian forest fires in February and the prolonged drought in Eastern Africa.

Research at the Met Office Hadley Centre, in collaboration with Oxford University, is pioneering a new way of tackling the issue by determining how human influence could have changed the odds of such extremes occurring. Such an approach was applied to the European heatwave of 2003 and used to show that it is very likely human influence has more than doubled the probability of such hot Europe-wide summer temperatures.

The weather associated with the forest fires in Australia in 2009 is also thought to have become more likely due to climate change. Australia has seen an overall warming in recent decades and Met Office research has attributed this to human influences.

A similar method can also be applied to cold weather events. For example, in early 2009 the UK had a spell of cold winter weather that had not been seen for a number of years. While we expect this kind of weather to continue even against a background of global warming, such events should become increasingly rare. This was borne out by the research, which showed cold European winters under the current climate would happen about once every 20 years, compared to once every five years in a climate without human influence.

These examples demonstrate that, while we continue to expect extremes of all types of weather, climate change is significantly altering the odds of them occurring. This is an important consideration for adaptation strategies. Research is ongoing to develop a system for attributing extreme weather events as they happen, providing an almost immediate assessment of how likelihoods have been affected by climate change. Such an attribution service would help societies cope with extreme weather by providing information to better understand the risks and how these are changing as a result of climate change.

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Dangerous climate change

The ultimate aim of the UNFCCC[1] is to prevent dangerous climate change. This means ensuring temperature rises allow ecosystems time to adapt naturally, do not put global food production at risk and permit sustainable economic development. Here, we look at four key issues which could jeopardise this aim:

- The decline of the great ice sheets and the associated sea-level rise.
- Dieback of the Amazon rainforest.
- The potential release of huge quantities of naturally stored greenhouse gases.
- Acidification of the world's oceans.

The impacts of these changes are potentially large and capable of affecting the entire planet. More significantly, once they have happened the effects are virtually irreversible over timescales of hundreds or even thousands of years.

A further concern is that we might already be committed to some level of these climate changes, which could themselves further accelerate warming and force even greater impacts.

We can reduce the risk of dangerous climate impacts by reducing global emissions of greenhouse gases.

[1] United Nations Framework Convention on Climate Change

- Both Greenland and West Antarctic ice sheets are shrinking
- Significant melting of either ice-sheet would cause considerable sea-level rise
- The Greenland ice sheet could melt beyond 'tipping points' from which it could not recover, causing irreversible sea-level rise
- Research is ongoing to see what effects global warming could have on the Antarctic ice sheet

LAND ICE

The Antarctic and Greenland ice sheets are vast, holding enough freshwater to cause sea-level rise of 73 metres if they were to completely melt. Large-scale decline of either ice sheet is not currently expected for centuries, but both the ice sheets are beginning to reduce in total mass, causing sea-level rise of about 0.5 mm a year. This is mainly due to calving of ice into the ocean at their outer edges.

Besides affecting sea-levels, this decline will also increase the amount of freshwater entering the oceans. Freshwater from the melting Greenland ice sheet may weaken ocean currents, such as the Gulf Stream, which are important for global redistribution of heat and water across our planet. Extra fresh water in the Antarctic causes the ocean to stratify, which could result in cooler ocean surface temperatures and thicker sea-ice. Impacts on ocean circulation are uncertain, however, and are the subject of ongoing research.

There is a danger that climate change could increase the rate of decline of either ice-sheet, which could bring rapid changes to sea-level and flow of freshwater into the oceans. This is a developing area of research, however, and models are currently being developed to produce more reliable projections of this process.

Greenland ice sheet

The Greenland ice sheet is the second largest in the world, covering an area of about 1.7 million km². Studies have already shown that if global warming continues unchecked the ice sheet could melt completely over the course of several thousands of years — raising sea levels by up to seven metres. However, Met Office research has shown the melting process could contain several 'tipping points'. When these are passed, the ice sheet would not be able to fully recover — even if CO_2 concentrations later return to pre-industrial levels. Using a sophisticated climate model coupled to a simulation of the ice sheet the research showed:

- If the ice sheet shrinks by more than 15% (which could occur within 300 years) it could be locked into a decline from which it would only recover to 80% of its current size. This would cause a 1.3 metre sea-level rise.
- If the ice sheet reduces to about 50% of its current size it would be locked into further reduction, only stabilising again at 20% of its current size — creating a sea-level rise of 5 metres.

Once these points are crossed, only an ice age would provide sufficiently cold temperatures for the ice sheet to fully recover and sea-level rises to be reversed. Current predictions estimate an ice age is unlikely to happen for tens of thousands of years.

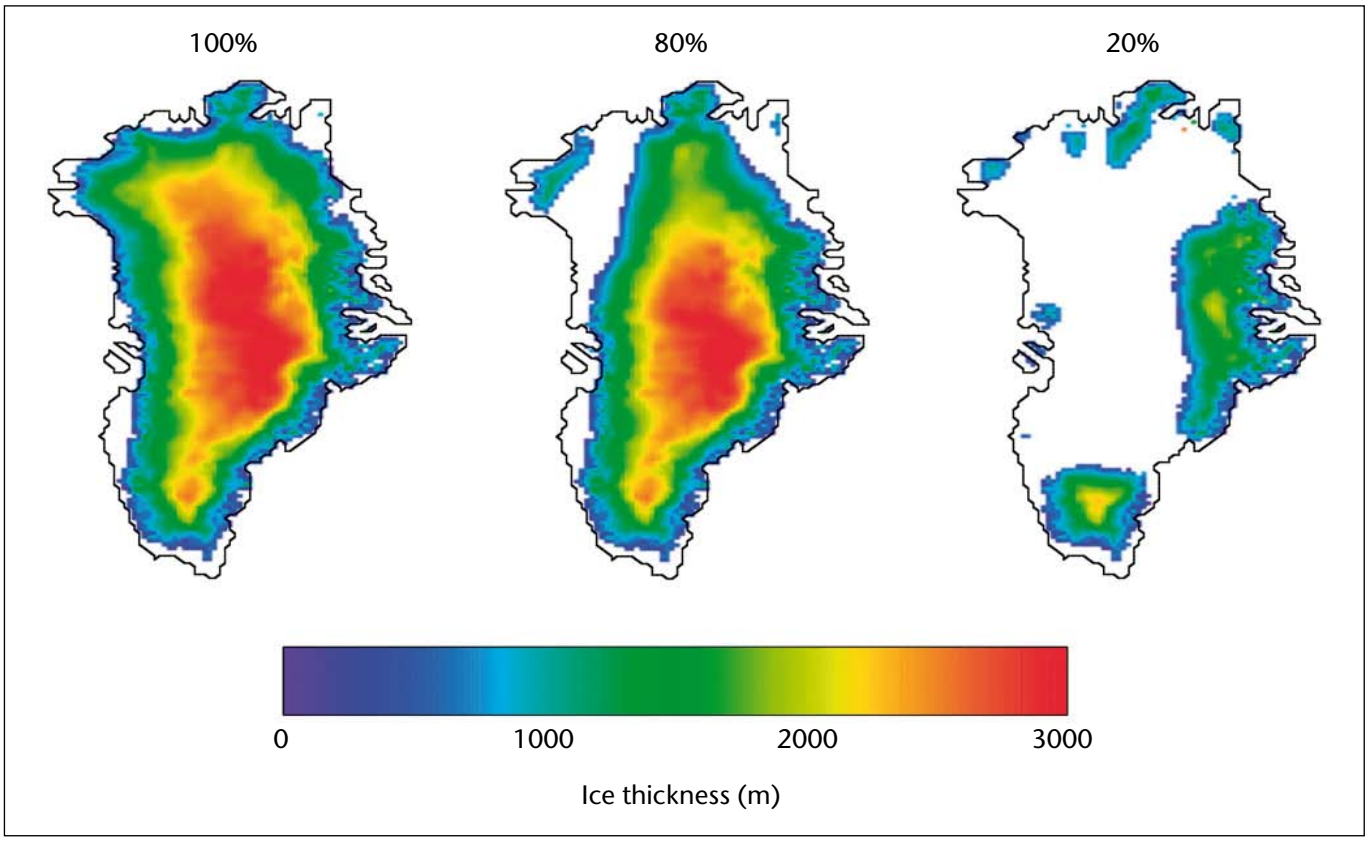


Figure 1. Ice thickness of three projected stable states of the Greenland ice sheet. The state obtained, on return to pre-industrial temperatures, depends on the extent of decline under global warming. If the ice shrinks by less than 15% the ice can fully recover. If it shrinks by between 15 and 50% it will stabilise at 80% of its current size. If it shrinks by more than 50% then it will stabilise at 20% of its current size.

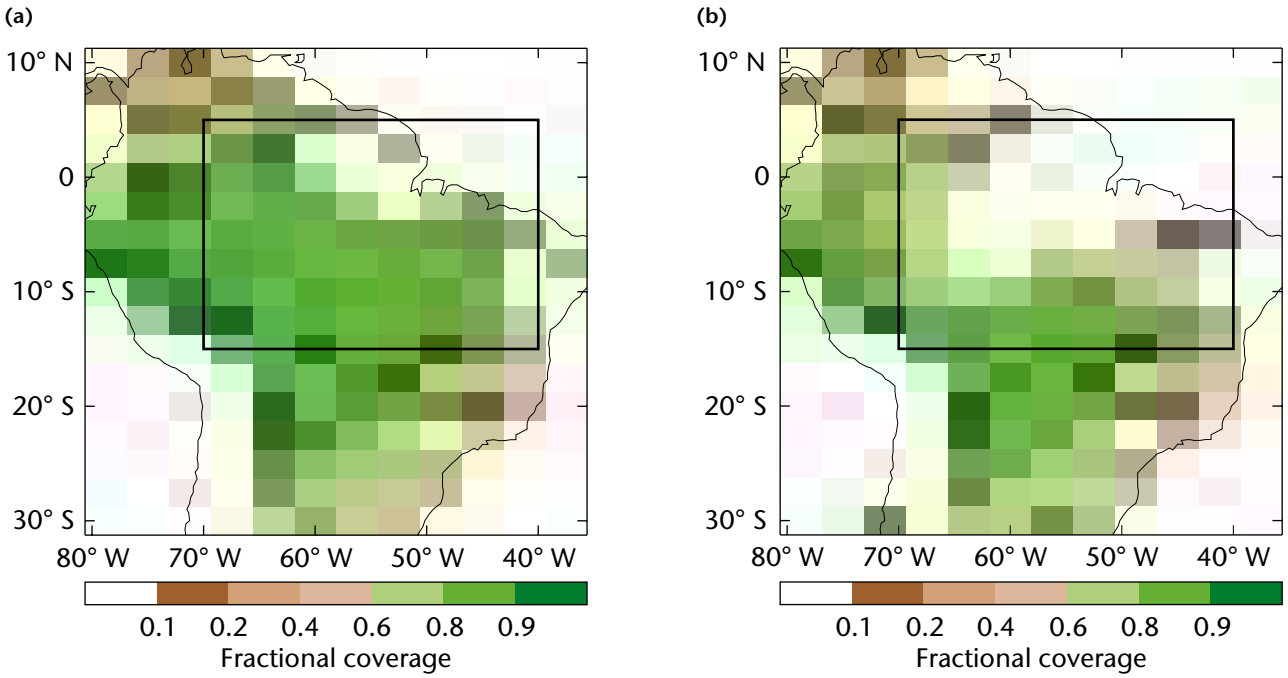


Figure 2. (a) Geographical distribution of Amazon fractional forest tree cover at 2040 when the global temperature rise reaches 2 ˚C.
(b) Committed distribution of fractional tree cover if 2 ˚C is sustained for 100 years.

AMAZON RAINFOREST

The forest in the Amazonia basin covers about 5.5 million km², an area far larger than India, and is an area of great biodiversity. It is a vital part of the global climate system, taking in and storing huge quantities of CO_2 from the atmosphere. As the forest diminishes, the stored CO_2 is released and there is a reduction in its capacity to absorb further atmospheric CO_2 — both factors which accelerate climate change.

Thousands of square kilometres of the Amazon rainforest are being cleared each year for human settlement and agriculture, a process which is estimated to be contributing an equal amount of CO_2 to the atmosphere as the world's entire transport sector. While human deforestation is a serious threat to the Amazon, this ecosystem is also one of the most vulnerable to climate change.

Climate modelling has shown how warming could reduce rainfall across the area and dry out soil, risking extensive forest dieback. Met Office research projected how Amazon vegetation would be affected by warming in the long-term. It revealed that the rainforest is likely to react slowly, with many impacts not being seen until about 2040. The forest continues to react for many decades after, however, even if global temperatures stabilise at particular level. This means the rainforest would be locked into significant change long before any changes are apparent, suggesting the scale of deforestation due to climate change could be far greater than previous estimates.

In the study, the Met Office climate model projected a small amount of committed dieback at a global temperature increase of about 1 °C sustained for 100 years. This increased significantly at 2 °C, at which point the forest declined by 20–40% (within the boxed area in Figure 2). At 3 °C, the decline was about 70%.

In the simulations, the forest took 500 to 2,000 years to fully recover (depending on the extent of the damage) even after temperatures had returned to pre-industrial levels. There is significant uncertainty over these figures, however, and understanding the process further remains a crucial research area. It is clear that when considering dangerous climate change we must look at not only short-term impacts, but also the long-term commitments.

It is likely that committed impacts such as those projected for the Amazon could apply to other ecosystems around the world, risking further irrecoverable damage to habitat and climate systems.

- Global warming could reduce rainfall and dry out soil in the Amazon, risking extensive dieback of the forest
- A sustained global temperature rise of more than 2 °C above the pre-industrial average could see the rainforest decline by 20–40%
- The rainforest is likely to react slowly to temperature change, but would then be committed to decline for decades — even if temperatures stabilise
- If our climate returns to its pre-industrial state, it could still take over 500 years for the rainforest to recover
- Decline of the rainforest could affect climate beyond South America and increase the pace of global climate change

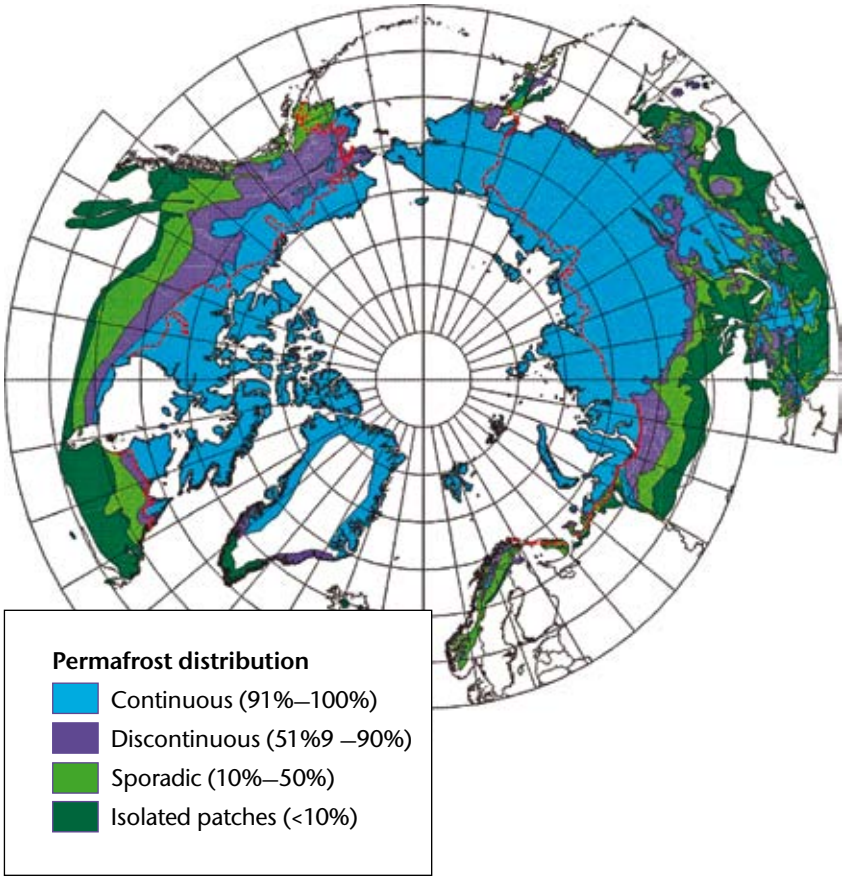


Figure 3. Distribution of permafrost in northern high latitudes. (Tarnocai C, Canadell JG, Schuur EAG, Kuhry P, Mazhitova G, Zimov S, Soil organic carbon pools in the northern circumpolar permafrost region. Glob. Biogeochem. Cycles, 23, doi:10.1029/2008GB003327, 2009. Copyright 2009 American Geophysical Union. Reproduced by permission of American Geophysical Union)

- Global warming could destabilise huge stores of methane stored under the oceans
- Destabilisation of organic-rich permafrost in northern latitudes could lead to the release of large quantities of CO_2 and methane into the atmosphere
- These could increase the speed and extent of climate change if released into the atmosphere
- The higher the temperature rise, the more exposed we become to risk of these stores being released
- These processes are not currently included in climate projections

METHANE

Although less abundant in the atmosphere than CO_2, methane is about 20 times more potent as a greenhouse gas. It has a comparatively short lifespan in the atmosphere — lasting about a decade compared to about a century for CO_2, but is nevertheless an important greenhouse gas with the potential to cause significant temperature change. There are two known environments where very large quantities of methane are currently either locked away or could be formed — deep under the oceans as methane hydrates, and in permafrost organic-rich soils in places such as Siberia. Global warming could destabilise these stores, however, releasing the stored carbon with potentially serious impacts for climate change.

Methane hydrates

Huge stores of methane hydrates are locked at depth in the oceans, where high pressure, low temperature, and the methane gas itself keep them stable. As our oceans get warmer it's possible this delicate balance could be upset, resulting in the release of methane from the water. Studies of the past climate going back over millions of years suggest previous releases of these stores may have played a role in abrupt and severe changes to climate.

Research is ongoing to establish the exact quantities of methane stored, at what point they may become unstable, and how much methane would be released if this happened. A Met Office Hadley Centre study looked at how projected temperature changes on the ocean bed could affect the stability of methane hydrates. Focusing on the expected area of greatest warming, in the Barents Sea, the study showed relative stability in the methane stores at the beginning of the forecast period in 1860, but by the end of the period, at 2100, there was a reduction or disappearance of this safe-zone.

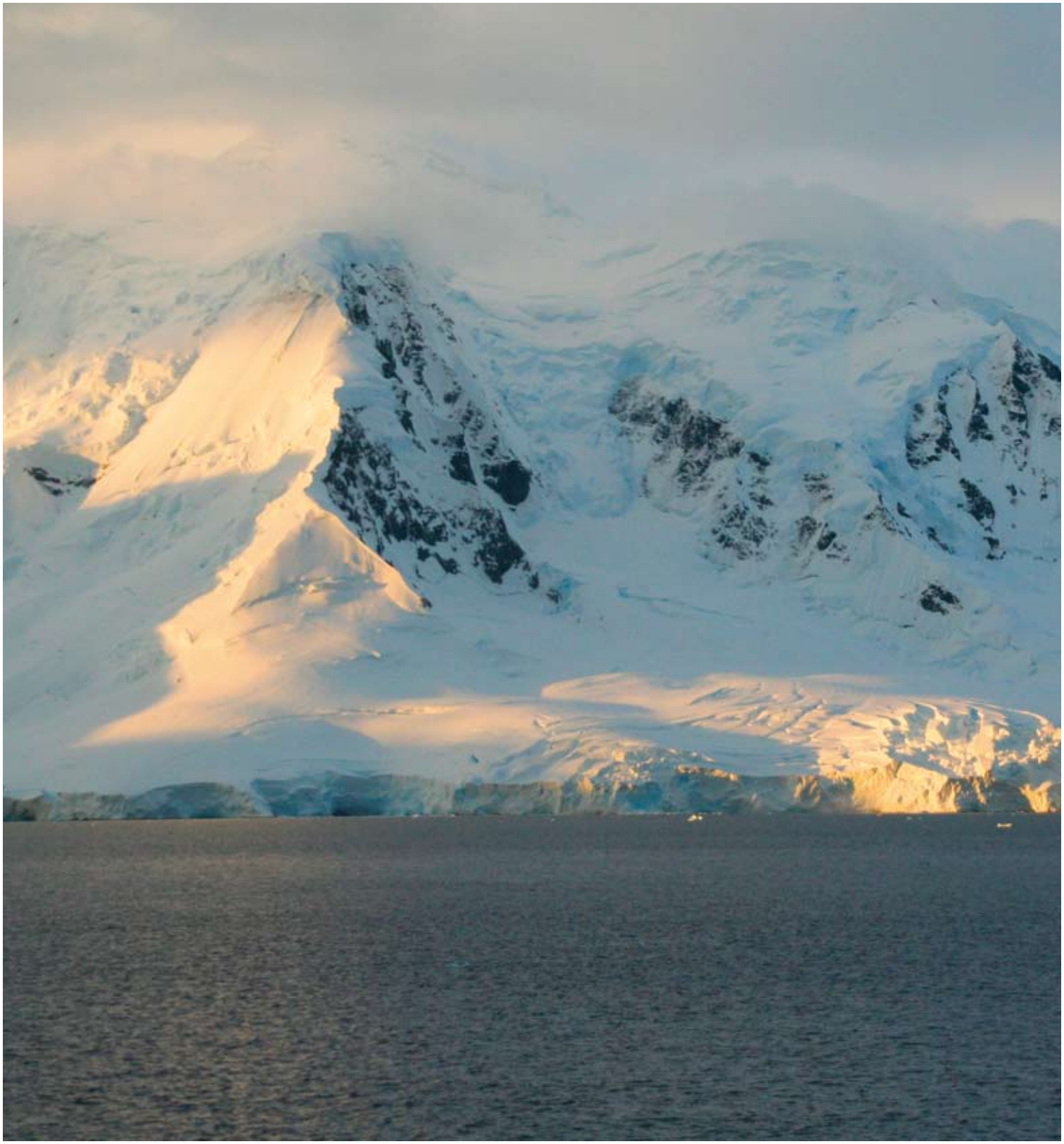
The current risk of methane hydrates being released is real but difficult to quantify. There is no firm assessment of how long it would take methane hydrate stores to destabilise on a global scale. Whereas several million years were required to create the stores, the decline due to warming may be comparatively rapid. Given that there is a long time-lag between climate warming and a resulting change in sea temperatures, there is a danger we could be committed to this risk for several centuries to millennia. If temperatures continue to rise, the level of risk will increase.

Permafrost methane

Frozen organic-rich soils in high latitudes contain large stocks of carbon which, if thawed, could decompose to form either methane or CO_2. When the permafrost thaws and dries out due to rising temperatures, these gases could be rapidly released into the atmosphere. This process has already been observed on a small scale in places such as Siberia. As these carbon deposits have accumulated over thousands or even tens of thousands of years, such rapid release would be effectively irreversible and could have a significant impact on our climate.

At the moment, there is no clear global picture of exactly how much of this frozen carbon could be released when the soil thaws, or to what extent it would be released as methane or CO_2. This uncertainty means the process is not yet included in climate predictions. It is an area of intensive research, however, and it is hoped this process will be included in Met Office climate predictions within the next five years.

Antarctica
Antarctica has two vast ice-sheets, the West Antarctic and the far larger East Antarctic. Combined they cover about 14 million km², an area larger than Canada, and if both were to melt completely the oceans would rise by 66 metres. There is uncertainty over how the ice sheets may melt, particularly as to whether there could be 'tipping points' of irreversible loss, and over what time scales this could occur. The Met Office is using expertise from its Greenland research to look into this area.



- The oceans are becoming more acidic as they absorb more CO_2 from an atmosphere with a higher concentration of greenhouse gases

- Changes in acidity could threaten numerous marine species throughout the food chain such as plankton, corals and crustaceans, disrupting marine ecosystems

- Increasing sea temperatures are also detrimentally affecting marine life

- As the oceans acidify they are less able to absorb further CO_2, accelerating climate change because more man-made emissions remain in the atmosphere

OCEAN ACIDIFICATION

Human activity has significantly increased the concentration of CO_2 in our atmosphere, causing it to rise from about 280 ppm (parts per million) before the industrial revolution to more than 380 ppm today, and it continues to increase. This not only contributes to global warming, but also has serious implications for ocean ecosystems through a process known as ocean acidification, measured by pH.

Ocean pH has already decreased (increasing acidity) from a pre-industrial average of ~8.2 to a present day level of 8.1. Future increases in CO_2 emissions will continue to decrease pH, with predictions estimating a decrease to 7.8 by 2100. Even the apparently small change from 8.2 to 8.1 means a large change in ocean chemistry with significant effects on marine organisms. In addition, as oceans acidify they are less able to absorb further CO_2, accelerating climate change.

The combination of increasing acidification and rising ocean temperatures poses a serious threat to many marine ecosystems and to human societies which currently rely on them. Research is underway into the impact of both ocean acidification and rising temperatures on the viability of marine ecosystems and the ability of the oceans to absorb CO_2 from the atmosphere.

Impacts of acidification on marine life

- Warm-water corals, important habitats for many other species, could dramatically decline. Research indicates warm-water coral reefs are likely to stop growing and start to dissolve by the time atmospheric CO_2 reaches 560 ppm.
- Plankton that form calcite or aragonite shells will find it increasingly difficult to do so in more acidic conditions, subjecting them to greatly increased environmental stress, increased danger from predators and higher mortality rates. Some of the affected plankton species (e.g. pteropods) play key roles in Arctic and Antarctic food chains which could be seriously disrupted.
- Other species which form shells are also likely to suffer a detrimental impact on their growth and metabolism. These include crustaceans (such as crabs, lobsters and shrimp), bivalves (such as scallops, clams and oysters), echinoderms (such as sea urchins) and cold-water corals.
- Larger species such as fish may be affected by acidification, both directly during their early life stages and through disruption to lower levels of the food chain.

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Options for mitigation: global analysis

- If emissions continue to rise, temperatures could rise by 4 °C[1] by the end of the century
- Early and rapid reductions in carbon emissions will give a good chance of keeping temperature rises below 2 °C
- Increases of 4 °C would have major implications, such as decreasing agricultural yields for all major cereal crops in all growing regions
- 4 °C of warming globally will mean an average of 5.5 °C over land and considerably more in some areas, particularly at middle and high latitudes

Man-made greenhouse gas emissions have been the main driver of the climate change we have seen over the past 40 years. These emissions will continue to affect our climate for many decades to come and a certain amount of further warming is inevitable because of the long lifespan of CO_2 in the atmosphere.

Crucially, however, if emissions are reduced early and rapidly the extent of climate change will be mitigated. On the other hand, if greenhouse gas emissions continue unabated, or increase, the implications of global warming grow more severe and pose ever greater risks to life on Earth.

Research has shown that it is the cumulative effect of greenhouse gases which is crucial in determining the extent of future climate change. Early and rapid reductions in greenhouse gas emissions can produce significantly lower cumulative levels and reduce the temperature rise projected to occur in the 21st century and beyond. Delaying cuts in emissions means even more rapid reductions would be needed later to achieve the same cumulative emissions and temperature target. These more rapid reductions may not be technically feasible or affordable.

To assess the possible impacts of climate change, several emissions scenarios are used to understand how we can influence our own future (Figure 1). The temperatures that could result from these different scenarios are shown in Figure 2, and it is clear the benefits of emissions reductions are potentially huge. The 'business as usual' scenarios show our climate warming beyond 2 °C between 2035 and 2055. There is a high probability that business as usual scenarios would push warming to 4 °C this century, and in the worst case this could come as early as 2060. With dramatic reductions in emissions, however, there is a good chance of

[1] compared with pre-industrial levels

There is a high probability that business as usual scenarios would push warming to 4 °C this century, and in the worst case this could come as early as 2060.

keeping temperature rises below 2 °C and they are unlikely to reach 3 °C.

Many previous studies used only simple climate models. The projections from the EU-ENSEMBLES project have been created using a number of state-of-the-art climate models. Their consensus gives us high confidence in the results, especially in light of the fact the outcomes agree with earlier studies using simpler models. Research is now focusing on using these complex models to look at the regional changes and impacts in more detail.

These model projections indicate that peaking emissions in the next 10 years and rapid reductions in emissions after this would give a 50% chance of temperatures staying below 2 °C. However there would still be a:

- 30% chance of temperatures rises staying over 2 °C for 100 years
- 10% chance of staying over 2 °C for 300 years

In addition, every delay of 10 years could add 0.2–0.5 °C to the temperature rise.

Figure 1. Cumulative emissions. The figure shows:

- 'Business as usual' scenarios that feature no mitigation policy: the SRES A1FI contains a continued heavy reliance on fossil-fuels, while SRES A1B features a more balanced use of fuel sources.
- A1B early peak scenario (from the AVOID programme) peaks emissions in 2016 before reducing them at 4% per year.
- E1 (from the EU-ENSEMBLES project) peaks greenhouse gas concentrations at just over 500 ppm before aiming towards a level of 450 ppm in the long term.

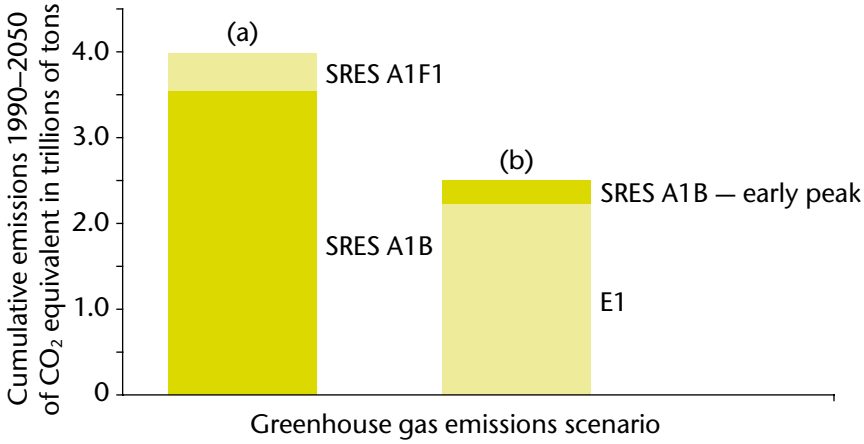
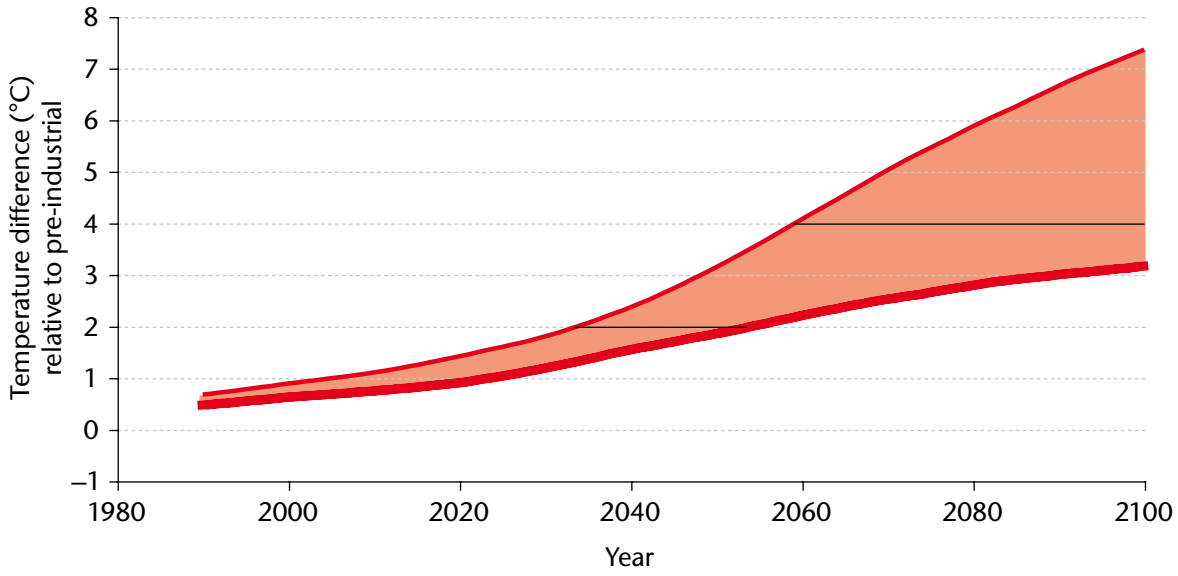
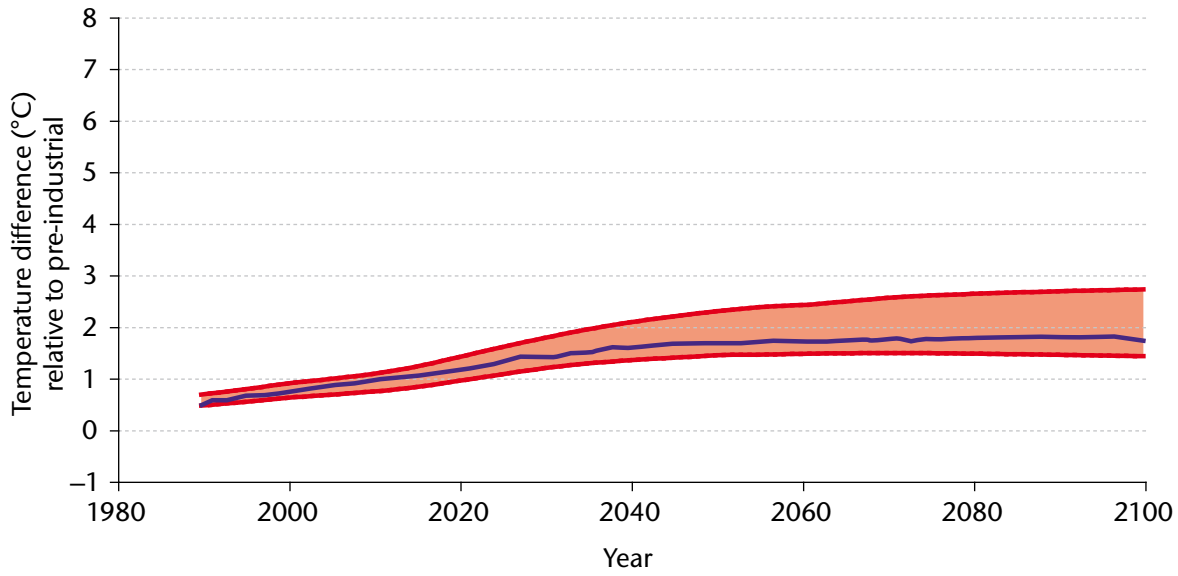


Figure 2. Impact of various emissions scenarios on temperature changes over the 21st century. **(a)** The range of possible temperature rises (relative to pre-industrial) for the A1B and A1FI scenarios. There is less than a 10% chance of temperatures remaining below the bottom curve for the A1B emissions scenarios and of going above the top curve for the A1FI emissions scenario. The horizontal lines highlight the range of time when temperatures rises might reach 2 and 4 °C. **(b)** The red area represents the 10–90% probability range of temperature rises for the A1B early peak scenario. The blue line is the average temperature rise from all the ENSEMBLES models running the E1 scenario.

(a)



(b)



The bigger the increase in global temperature, the more exposed we become to the risk of passing irreversible thresholds and causing dangerous climate feedbacks.

CONSEQUENCES OF DANGEROUS CLIMATE CHANGE

Global changes in temperature will not cause a uniform warming across the planet — instead there will be wide variations across regions. This is particularly stark for 4 °C of global warming, with rises of 3 °C in some parts of the ocean and up to around 15 °C in the Arctic. Overall the land temperature rise is 5.5 °C. This could focus the impacts of global warming on particular areas, drastically altering regional climates and severely disrupting ecosystems.

Many impacts of climate change are progressive as temperatures increase, for example increased flooding and drought. However, higher temperatures are more likely to pass dangerous thresholds in the climate system. These tipping points include irreversible loss of the Greenland ice sheet, which would lead to similarly irreversible sea-level rise. There are also potentially dangerous feedbacks, such as the possible release of huge quantities of greenhouse gases from marine hydrates and permafrost. The bigger the increase in global temperatures, the more exposed we become to the risk of passing irreversible thresholds and causing dangerous climate feedbacks.

Maps of temperature change and associated impacts for a global rise of 2 °C and 4 °C are shown on the accompanying large maps. The focus here is on impacts that directly affect people and more detail is given for 4 °C than 2 °C.

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Options for mitigation: sector analysis

- Civil aviation currently accounts for about 2.6% of global fossil-fuel emissions of CO_2
- Contrails made by high flying aircraft have a net warming effect on global climate, although this effect is probably smaller than previously thought
- Observed evidence shows contrails can develop into high-level cirrus clouds, which may have a larger net warming effect
- More research is needed on aviation-induced cloudiness to quantify its importance

There are a several ways to reduce the amount of greenhouse gases in the atmosphere and mitigate climate change. In order to ensure these are effective, however, it's important to understand the full consequences of action taken. Research provides the vital information needed to inform these choices and enable careful planning for mitigation strategies.

Here we look at the impact of the shipping and aviation industries, as well as black carbon. These areas raise the complex issues of trying to compare the impacts of pollutants that have very different effects and timescales in the atmosphere. These issues will become increasingly important as greenhouse gas emissions are reduced from the bigger polluting sectors, in particular CO_2 from the energy sector.

AVIATION

Civil aviation currently accounts for about 2.6% of global fossil-fuel emissions of CO_2, but the relative importance of aviation emissions is expected to increase significantly in the future due to rapid aviation industry growth and reductions in greenhouse gas emissions from other sectors. While significant, this contribution to CO_2 emissions is not the only impact aviation has on our climate.

Water vapour in the hot, moist exhaust from high flying aircraft can trigger condensation trails, known as contrails. They are normally short-lived, but — depending on atmospheric conditions — they can last much longer. Observational evidence shows contrails can develop into high-level cirrus clouds. Figure 1 shows a series of infrared satellite images from March 2009. Coil shaped contrails from an aircraft circling over the North Sea are seen to evolve into cirrus clouds covering a large part of eastern England. The 'aviation-induced clouds' become indistinguishable from natural cirrus clouds.

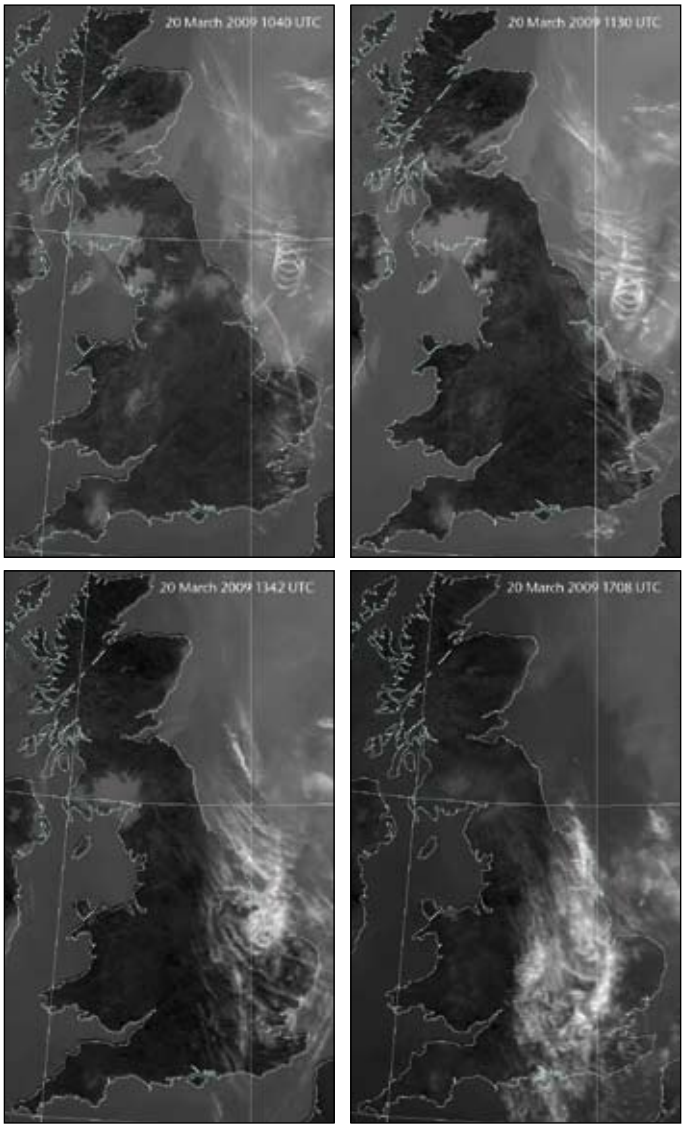
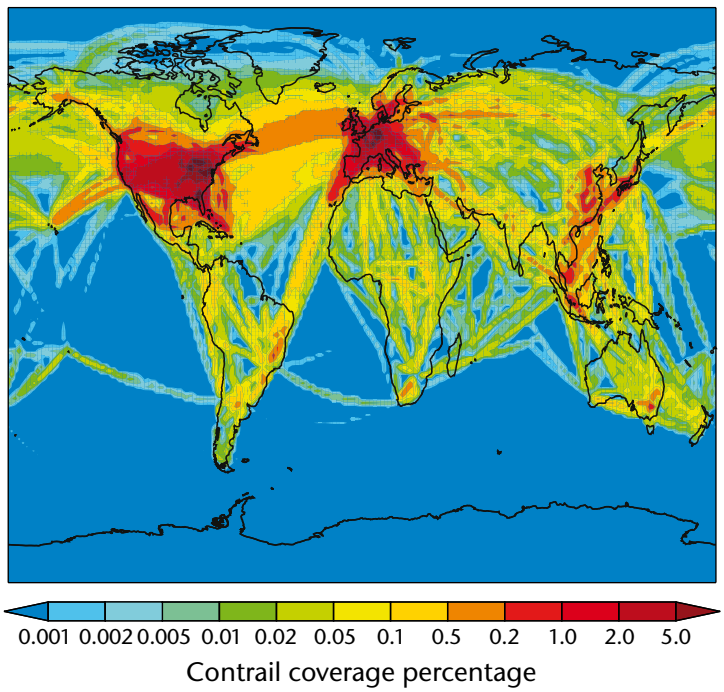


Figure 1. Satellite infrared images (20 March 2009 at 1040, 1130, 1342, 1708 UTC) showing the evolution of cirrus from contrails over the North Sea. (NOAA (US National Oceanic and Atmospheric Administration), NASA (National Aeronautics and Space Administration) and EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)).



Contrails and aviation-induced cirrus have two competing effects on climate: they reflect sunlight back into space to create a cooling effect, but also trap thermal radiation to create a warming effect. Studies show that, overall, the warming effect is stronger.

Climate model simulations allow the distribution of contrails to be mapped and their warming effect is now estimated to be smaller than initially thought. However, when it comes to aviation-induced cloudiness there is still considerable uncertainty about its geographic extent. This means there is also uncertainty in the amount of additional warming this process creates. Areas of high aviation activity are those most likely to be affected and research is ongoing to get a better understanding of the global impacts.

Figure 2. Climate model simulations of contrail coverage. (Rap A, Forster PM, Jones A, Boucher O, Haywood JM, De Leon RR, Bellouin N, Parameterisation of contrails in the UK Met Office Climate Model, submitted to J. Geophys. Res., 2009).

- Shipping accounts for around 3.4% of global fossil-fuel emissions of CO_2, contributing to global warming
- Fuel used for shipping has a high sulphur content which, when burnt, acts as a global coolant by reflecting sunlight back into space
- Overall, shipping has a cooling effect in the short-term but a warming effect in the long-term
- Sulphur in shipping fuel will be reduced due to international rules, bringing a warming effect; the extent of this is under investigation

SHIPPING

Shipping accounts for around 3.4% of global fossil-fuel emissions of CO_2, and emissions are growing at around 3% per year. This is a significant contribution to global greenhouse gas emissions, but shipping is currently not included in the Kyoto protocol.

Besides CO_2 emissions, shipping has another impact on global climate due to the relatively high sulphur content of the fuel used. When burnt, shipping fuel releases a high amount of sulphur dioxide which then reacts to form sulphate aerosols in the atmosphere. These act as a global coolant by reflecting sunlight back into space.

Model simulations have shown that, after both the warming effect of CO_2 emissions and the cooling effect of sulphate aerosols are taken into account, shipping has created a net cooling effect on the climate. Shipping emissions are therefore helping to cool the planet in the short term, although the extent of this cooling is uncertain. The sulphate aerosols are removed fairly quickly from the atmosphere in rainfall, whereas the CO_2 continually builds up. After about 50 years the warming from the accumulated CO_2 overcomes the cooling from the sulphate.

Sulphate aerosol is also an air pollutant, harmful to both humans and plants (through acid rain). New international rules aim to reduce its damaging effects by significantly reducing the sulphur content in shipping fuel. While this will tackle air pollution by removing the aerosols, this will have a warming effect on our climate. The Met Office is currently researching the climate impacts of reducing the sulphur content of shipping fuel to get a clearer understanding of the overall impact on climate change.

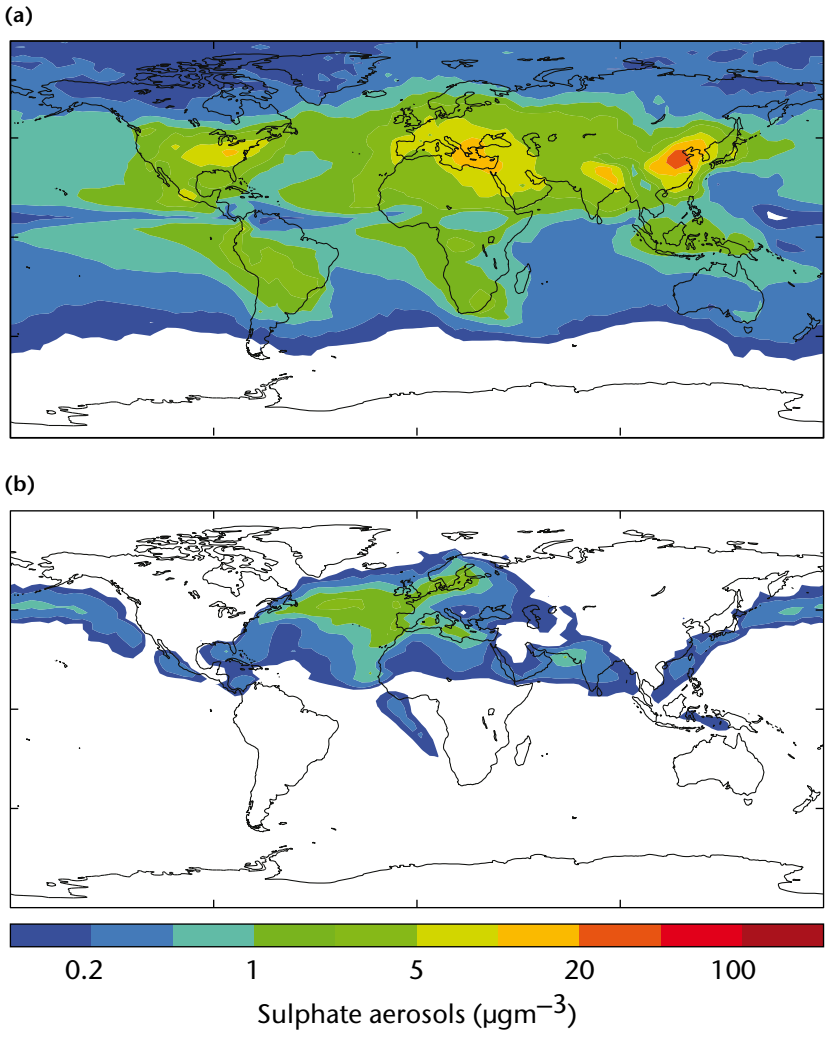
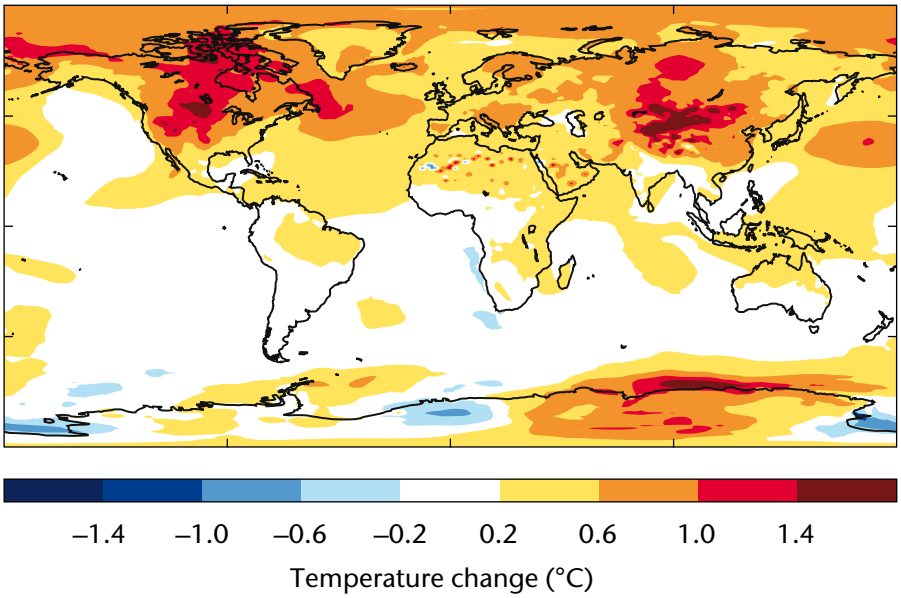


Figure 3. Global distribution of the sulphate aerosols (in micrograms per cubic metre) due to **(a)** all human activities except shipping and **(b)** due to shipping, in the year 2000 as calculated by the Met Office Hadley Centre model. This shows that shipping contributes to a significant fraction of sulphate pollution particularly in northern mid-latitudes.

Figure 4. Change in near-surface temperature (°C) due to changes in human emissions of black carbon from fossil fuel combustion between 1860 and 2000 from the Met Office Hadley Centre climate model. This does not include the snow darkening effect.



- Black carbon is an air pollutant which damages human health
- Although it has a short lifespan of about 15 days, black carbon also has a dual warming effect on climate: it absorbs sunlight when in the atmosphere and darkens reflective surfaces, reducing the amount of sunlight they reflect back in to space
- This darkening effect is particularly significant in the Arctic
- Black carbon is often released with other greenhouse gases and aerosols, which have contrasting effects on our climate, meaning mitigation measures must be assessed carefully

BLACK CARBON

Black carbon, or soot, is a by-product of combustion. The main sources are energy generation and transport, but many sources such as domestic cooking and slash-and-burn forest clearance also contribute. It enters the air as fine particles produced by incomplete burning, and has serious effects on air quality and human health. It has a relatively short lifespan in the atmosphere of about 15 days, compared to about 100 years for CO_2.

The drive to reduce pollution led to particulate matter being targeted by air quality control policies across Europe and North America decades ago. As a result, today's emissions of black carbon across both continents are about 60% of their 1950 levels. In contrast, developing countries have seen a big increase in emissions. About a third of total global black carbon output is attributed to the Indian subcontinent and China according to current estimates.

Black carbon has a dual warming impact on our climate. Firstly, it absorbs a large fraction of the sunlight it comes into contact with. Secondly, when black carbon settles on reflective surfaces it darkens them and reduces the amount of sunlight they reflect. In both cases, the end result is that more of the sun's energy is absorbed.

The darkening effect is particularly important for snow and ice, where reflectivity is significantly reduced. In such cases, the darkening process causes local warming which melts the ice and snow, eventually revealing the darker surfaces below to cause further warming. This can impact the Arctic, which is affected by black carbon emitted from Europe, North America and Asia.

It is thought warming due to black carbon absorbing sunlight is about one fifth of that due to CO_2, but its impact on darkening reflective surfaces could be more significant regionally – particularly in the Arctic. The overall warming effect, compared with that of other greenhouse gases, is still being quantified.

The short lifetime of black carbon means any reduction in emissions would rapidly reduce the amount of black carbon in the atmosphere. Combined with its disproportionate effect on the Arctic, this tends to make black carbon an attractive target for mitigating climate change in complement to reduction in greenhouse gas emissions.

There are other issues to consider, however. Black carbon tends to be emitted with other types of aerosol which have a cooling effect on our climate. Most reductions in black carbon emissions would therefore be accompanied by reductions in cooling particles so that the net effect would be less than anticipated from the reduction of black carbon alone. Moreover, if emissions reductions of black carbon are accompanied by an increase in CO_2 emission, then the trade-off between the short-term cooling and the long-term warming has to be assessed carefully.

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